NASA TECHNICAL NOTE

NASA TN D-5730

c. 1

NASA TN D-5730

PARAMETRIC STUDY OF A FRANGIBLE-TUBE ENERGY-ABSORPTION SYSTEM FOR PROTECTION OF A NUCLEAR AIRCRAFT REACTOR

by Richard L. Puthoff and Klaus H. Gumto

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1970

1. Report No.
NASA TN D-5730

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle PARAMETRIC STUDY OF A FRANGIBLE-TUBE ENERGY-ABSORPTION SYSTEM FOR PROTECTION OF A NUCLEAR AIRCRAFT REACTOR

5. Report Date
March 1970

6. Performing Organization Code

7. Author(s)
Richard L. Puthoff and Klaus H. Gumto

8. Performing Organization Report No.
E-4991

9. Performing Organization Name and Address
Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio 44135

10. Work Unit No.
126-15

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

13. Type of Report and Period Covered
Technical Note

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract
A parametric study for determining the minimum system weight was made of an omnidirectional energy absorbing system utilizing frangible tubes. The system typified that which might be applied to a nuclear airplane. Variables affecting energy absorber weight, in order of decreasing importance, are angular dependence, specific energy absorption, frontal impact velocity, deceleration rate, number of tubes, and ratio of tube diameter to franging die radius. From the parametric curves generated, a frangible-tube energy-absorption system of a particular design concept studied for a 300 MW powerplant (for a 1 to 1.5 million lb (450 000 to 680 000 kg) nuclear airplane) would weigh at least 50 percent of the powerplant weight for impact velocities of 400 ft/sec (122 m/sec) from the front and 250 ft/sec (76 m/sec) in all other directions.

17. Key Words (*Suggested by Author(s)*)
Energy absorption
Nuclear airplane
Frangible tubes
Nuclear safety

18. Distribution Statement
Unclassified - unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	36	$3.00

*For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151

PARAMETRIC STUDY OF A FRANGIBLE-TUBE ENERGY-ABSORPTION SYSTEM FOR PROTECTION OF A NUCLEAR AIRCRAFT REACTOR

by Richard L. Puthoff and Klaus H. Gumto

Lewis Research Center

SUMMARY

The reactor containment vessel of a nuclear airplane must contain the fission products even at ground impact. In this study frangible-tube energy absorbers are used to absorb the energy at impact and to prevent rupture of the containment vessel. Frangible tubes were selected because tests show that they absorb more energy per pound of absorber than other known energy absorbers.

A parametric study for determining the minimum system weight was made of an omnidirectional energy-absorption system utilizing frangible tubes. The system, composed of tubes, dies, and supporting structure, typified that which might be applied to a nuclear airplane. The results of the parametric study are the following:

1. Increasing the absorber angular capability or increasing the specific energy of a frangible tube substantially decreases the energy absorber system weight. Variables of lesser effect but still of significance are the frontal impact velocity and the deceleration of the protected package.

2. Changing the number of tubes or the ratio of tube diameter to die forming radius has a minor effect on system weight.

From the parametric curves generated, a frangible-tube energy-absorption system would weigh 50 percent of the powerplant weight. This assumes an impact velocity of 400 feet per second (122 m/sec) in the frontal direction and 250 feet per second (76 m/sec) in all other directions.

The most promising method to reduce weight appears to be increasing the energy absorber operating angle and design integration of the reactor, shielding, containment vessel energy absorber, and aircraft structure. In this manner the system component serves both in its intended use during normal system operation and as an energy absorber during impact.

INTRODUCTION

Nuclear airplanes have the potential to provide longer range than chemical aircraft. However, before the nuclear airplane can be used it must be accepted as being safe.

Some of the safety problems connected with a nuclear aircraft are similar to a ground-based powerplant while others are uniquely different. The major difference is that the aircraft reactor is in motion and has the potential of crashing. To permit operation near populated areas the containment vessel must remain intact and contain all fission products upon impact with the ground or another aircraft. The containment vessel and the reactor contained within it have an enormous amount of kinetic energy when traveling at high speeds. To prevent rupture of the containment vessel the kinetic energy must be absorbed and the containment vessel decelerated at a rate which does not overstress the containment vessel walls. To accomplish this, the vessel is surrounded by an energy-absorption material.

Energy absorbers have been used most recently to provide soft landings for space vehicles on lunar or planetary surfaces (refs. 1 to 3). In this application the energy absorbers considered were material deformation, gas bags and gas-filled collapsible shells.

The requirements for a candidate energy-absorption system studied in this report are (1) impact speeds to 600 feet per second (183 m/sec), (2) minimum weight, and (3) availability of test data. An energy absorber with the potential to meet these requirements is the frangible tube (ref. 4). This device was selected because (1) it has been tested to specific energies (amount of energy that can be absorbed by 1 lb of energy absorber) of 38 500 foot-pounds per pound (115 500 J/kg), which is twice that of other energy absorbers, and (2) it has a potential to double these values. The weakest feature of the frangible tube is that it is essentially a unidirectional energy absorber. A single tube has only about $\pm 5^{\circ}$ angular capability. However, a low angular capability is common to all deformable structure energy absorbers. To increase directional capability, these tubes must be integrated into a system capable of taking some lateral loading.

The specific energies quoted in the literature for frangible tubes are based on tube weight only. In a flight system, die weight and associated support structure weight will add to the tube weight, thus reducing the specific energy. Only through a system analysis can these weights be defined. The purpose of this report, therefore, is to analyze the frangible tube, integrate it into an energy-absorption system for the protection of the containment vessel, calculate the total weight of the system, determine the system specific energy, and identify which design parameters most affect system weight. The parameters that will be studied are velocity at impact, deceleration rate, ratio of tube diameter to die radius, angular capability, number of tubes, and the specific energy of the tubes.

SYMBOLS

A	area, in.^{2} (cm^2)
a	acceleration, ft/sec^2 (m/sec^2)
D	diameter, in. (cm)
E	modulus of elasticity, psi (N/cm^2)
F	force, lb (N)
g	gravitational constant, 32 ft/sec^2 (9.85 m/sec^2)
L	tube length, in. (cm)
N	number of segments
P	pressure, psi (N/cm^2)
R	die forming radius, in. (cm)
r	radius, in. (cm)
S	stroke, in. (cm)
spe	specific energy, ft-lb/lb (J/kg)
t	wall thickness, in. (cm)
v	velocity, ft/sec (m/sec)
Δv	velocity change, ft/sec (m/sec)
w	weight, lb (kg)
ρ	density, lb/in.^{3} (kg/m^3)
σ	stress, psi (N/cm^2)

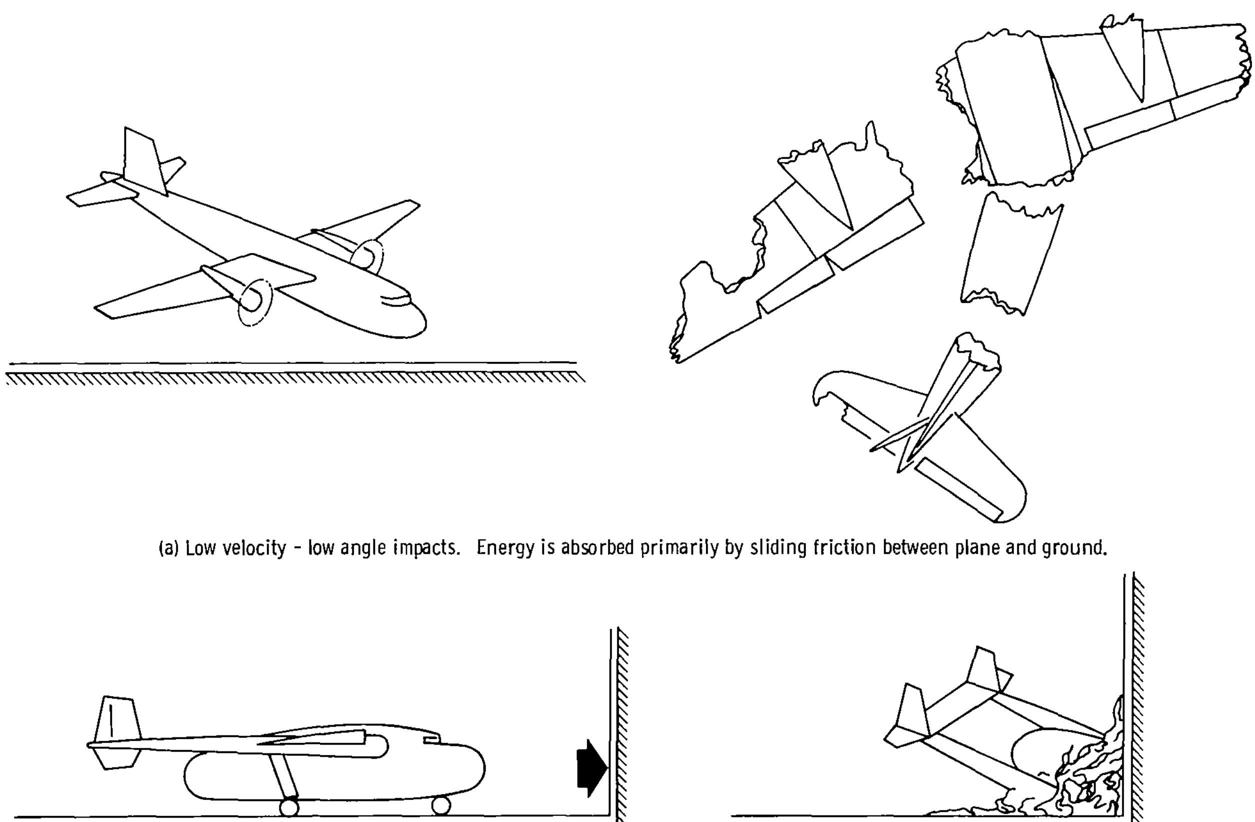
Subscripts:

b	bulkhead
d	die
ds	die shank
F	franging
f	final velocity
i	initial inside diameter
im	impact
o	outside diameter

p	protected package
s	shear
sys	system
t	tube
y	yield

DESCRIPTION OF PROBLEM

One of the phases of the crash sequence is the ground impact phase, which starts when the aircraft contacts the ground. If the impact occurs as the result of a midair collision or structural failure, the aircraft can strike the ground at any angle, thus making the velocity difficult to determine. Even if the aircraft is intact on contact with the ground, the angle of impact and the velocity can still vary over a wide range. In this



(a) Low velocity - low angle impacts. Energy is absorbed primarily by sliding friction between plane and ground.

CD-10656-10

(b) High velocity - high angle impacts. Energy is absorbed primarily by deformation of material.

Figure 1. - Typical types of aircraft impacts.

report, the containment vessel is assumed to be able to strike the ground at any angle, and a range of velocities is considered.

Figure 1 illustrates the two major types of aircraft crashes: low velocity - low impact angle, and high velocity - high impact angle. In the low velocity - low impact angle impacts, the energy is absorbed primarily by sliding friction between the aircraft and the ground. For such an impact, the aircraft may break up into several large pieces. In the high velocity - high angle impacts, the aircraft kinetic energy is absorbed by deforming or crushing the aircraft structure. Energy absorbers are required for this type of impact.

The major characteristics of passive energy absorbers are (1) they do not have to be activated or triggered, (2) they are ready to absorb energy at all times, and (3) they do not interfere with the operation of the aircraft. The following sections explain how frangible-tube energy absorbers work, review experimental data, and describe the design of an energy-absorption system.

FRANGIBLE-TUBE ENERGY ABSORBER

Energy-Absorption Mechanism

Frangible tubes utilize a fragmenting tube process in which energy is absorbed through the force developed when a frangible tube is pressed over a die (see fig. 2).

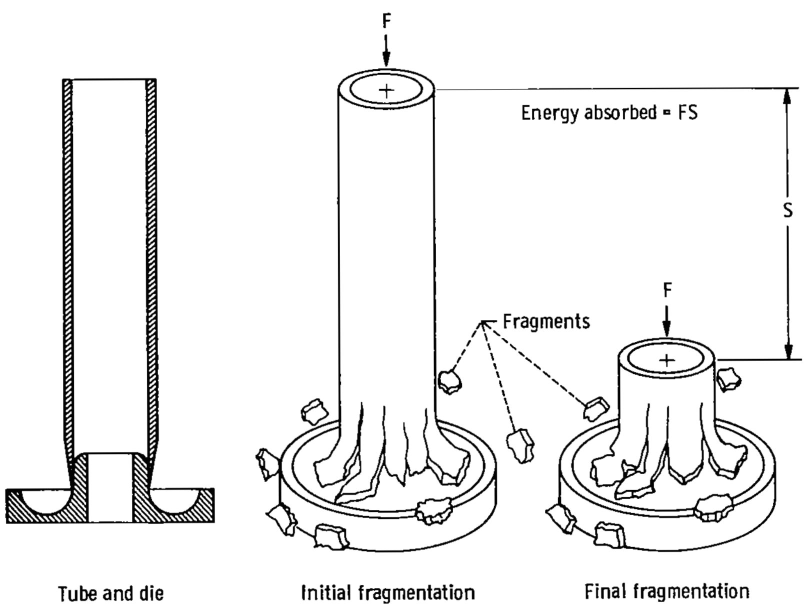
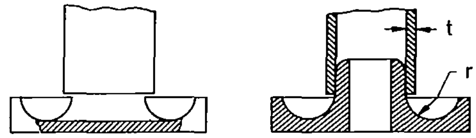
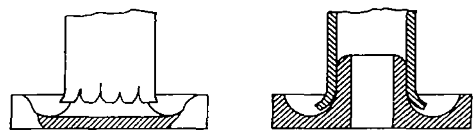


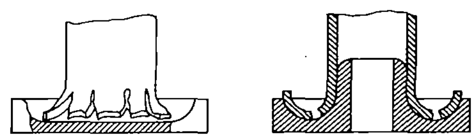
Figure 2. - Fragmenting process.



(a) Tube engaging on taper of die.



(b) Stretching of tube-strain energy due to hoop tension.



(c) Tube curving with radius-strain energy due to bending.

Figure 3. - Fragmenting tube process.

CD-10659-02

This process has been both structurally analyzed (ref. 5) and experimentally evaluated (ref. 4) to determine the performance of frangible tubes. Analytically, the process can best be explained by the use of figure 3. There are three stages that occur in the fragmentation process:

(1) Initially the tubes engage the die on a tapered surface above the die radius as illustrated in figure 3(a).

(2) As the tube is forced onto the die, stretching occurs and wall thicknesses are reduced. As a result, local failure occurs due to hoop tension in the tube (ref. fig. 3(b)).

(3) Continued travel of the tube results in the lip of the tube rolling up within the die radius with subsequent fragmentation of the strips as shown in figure 3(c).

Energy is absorbed in the fragmentation process by plastically deforming the material beyond its yield point.

The amount of energy that can be absorbed is determined by the yield strength and ductility of the tube material and by the design of the die. Mathematically the energy absorbed can be expressed by

$$\text{Energy} = (\text{Force})\ (\text{Stroke}) = FS \tag{1}$$

$$\text{Specific energy} = \frac{(\text{Force})\ (\text{Stroke})}{\text{Weight}} \tag{2}$$

Now in the case of the fragmenting tube, a franging stress is defined as the applied axial force necessary for the franging process divided by the tube cross-sectional area. Therefore,

$$\sigma_F = \frac{\text{Force}}{A_t} \tag{3}$$

$$\text{Energy} = \sigma_F A_t S \tag{4}$$

and the weight of the tube franged is $\rho_t A_t S$. Finally, the specific energy is based only on tube weight:

$$\text{Specific energy} = \frac{\sigma_F A_t S}{\rho_t A_t S} = \frac{\sigma_F}{\rho_t}$$

Thus, the specific energy obtained from a tube is a function of the franging stress to density ratio of the material. With a properly designed die the franging stress approaches the yield stress of the material. As a limit, the maximum expected possible specific energy is the yield stress to density ratio σ_y/ρ_t. For comparison of materials this value is often used. Table I illustrates yield stress and density values of some promising materials having high energy-absorption capability. Although the σ_y/ρ_t ratios shown are encouraging in comparison with current technology, it must be noted that the mechanism of franging a tube is not well known. Therefore, the performance falls short of the potential σ_y/ρ_t values.

Frangible tubes, however, appear to have a unique characteristic over many other energy absorbing devices in that the specific energies recorded in laboratory tests do more closely approach the maximum possible specific energy of the material σ_y/ρ_t. Honeycomb structures, for example, use the same materials as the frangible tube (e.g., aluminum, maraging steel), but their recorded specific energies fall far short of the material's σ_y/ρ potential. Measured frangible tube specific energies are, at present, about 60 percent of the maximum possible.

Tube Specification and Selection

The capability of the tube then is based primarily on the specific energy it develops. More specifically, it is the ratio σ_F/ρ_t. Although the franging stress is dependent on both the tube material and die design, with a properly designed die, the greater the yield strength of the tube the greater the σ_F.

TABLE I. - MAXIMUM ENERGY ABSORBING CAPABILITY OF CANDIDATE MATERIALS

Material	Yield stress, σ_y, psi (N/cm^2)	Density, ρ, lb/in.^{3} (kg/cm^3)	Maximum energy absorption capability, σ_y/ρ, ft-lb/lb (J/kg)
Maraging steel (18 Ni maraging)	300 000 (206 000)	0.289 (0.798×10^4)	86 500 (259 000)
Plastic[a] ("E" glass fabric and epoxy)	60 000 (41 300)	0.065 (0.179×10^4)	77 000 (230 000)
Titanium (6Al-4V titanium alloy)	126 000 (86 600)	0.160 (0.443×10^4)	65 600 (196 400)
Steel alloy (AISI 4130)	210 000 (144 800)	0.283 (0.783×10^4)	61 800 (185 000)
Aluminum alloy (7075-T6)	73 000 (50 300)	0.100 (0.277×10^4)	60 800 (182 000)
Aluminum (2024-T3)	42 000 (29 000)	0.100 (0.277×10^4)	35 000 (104 800)
Magnesium (AZ31B - H24)	16 000 (11 000)	0.0639 (0.177×10^4)	20 900 (62 500)

[a]E-glass filament wound plastic material has greater yield stress. However, E-glass filament wound tubes were tested in ref. 9 and had lower energy absorbing capability than the E-glass fabric tubes.

The candidate materials selected from table I whose franging stress σ_F would appear to be the highest are maraging steel, titanium, and aluminum. Plastic material also shows good σ_y values which would indicate high franging stress σ_F.

Review of Frangible-Tube Experimental Data

There has been some experimental work conducted by Langley Research Center on frangible tubes (ref. 2). Results of this effort can be summarized as follows:

(1) The average franging stress varies directly as the ratio of the tube wall thickness to die forming radius t_t/R.

(2) The maximum franging stress occurs at t_t/R ratios of 0.6 to 0.65 depending on the material. When t_t/R becomes greater than these values, franging stops and the tube fails by splitting and buckling.

(3) For 2024-T3 aluminum alloy tubing, the franging stress varied directly as the cube root of the ratio of the tube inside diameter to die forming radius D/R at a constant t_t/R ratio.

(4) AISI 4130 steel was the most efficient tubing tested on the basis of specific energy absorption.

(5) Energy-absorption capabilities of various materials increase with increasing material yield stress.

For a high performance tube design, the material selection and die design play an important role. In reference 4, AISI 4130 steel tubing demonstrated the highest specific energy of the materials tested. When operation was at a t_t/R ratio of 0.6, a specific energy of 37 000 foot-pounds per pound (111 000 J/kg) or 60 percent of its yield was recorded. If the franging stress were equal to its yield, energies of about 62 000 foot-pounds per pound (185 000 J/kg) would be possible when using AISI 4130. If maraging steel tubes were franged at their yield stress of 300 000 psi (206 500 N/cm^2), specific energies to 86 500 foot-pounds per pound (259 500 J/kg) would be possible.

As cited in reference 4, however, the final consideration is the ability of the tube to fragment. High yield stresses do not ensure a fragmenting process. In some cases, tube buckling can occur prior to fragmentation. Unfortunately, the mechanical properties of a material required for fragmentation are not well understood, and, as a consequence, the maximum σ_F obtained to date is about 60 percent of σ_y.

Frangible-Tube Design

The two basic requirements in designing a frangible tube for an energy absorbing system are to (1) absorb the kinetic energy of the package to be protected and (2) to provide the desired deceleration rate during this process. These are independent requirements. The deceleration during slowing down is related only to the initial impact velocity and the allowable stopping distance; namely,

$$a = \frac{V_{im}^2}{2S} \tag{6}$$

The weight of the package does not affect the deceleration nor does the specific energy of the tube (assuming all the kinetic energy is dissipated by the energy absorber in the stroke specified). The weight of tube required to decelerate the package is a function of the kinetic energy of the impacting package and the tube specific energy; that is,

$$\text{Tube weight (lb)} = \frac{\text{Kinetic energy}}{\text{Specific energy of tube}} \tag{7}$$

The kinetic energy is expressed by

$$KE = \frac{1}{2}\frac{w}{g}V_{im}^2 \tag{8}$$

where w is weight of impacting package plus the weight of the tube and die. With equations (6) and (7) satisfied, the tube and die are dimensioned to be compatible with force, t_t/R, and σ_F requirements. In addition, a length to diameter ratio is imposed on the tube to ensure that it will not buckle. A detailed derivation of these relations is presented in appendix A.

Frangible-Tube Operating Angular Limitation

The frangible tube is quite sensitive to the direction the force is applied to the tube axis (estimated angular capability, $\pm 5^{\circ}$). As this angle increases, the tube will cease franging and will begin buckling. Therefore, if the angle of the applied force is unknown, several tubes must be distributed throughout the solid angle. This tube grouping (hereafter called a segment) performs in the same manner as a single tube; that is, the total number of tubes absorb the total impact energy.

ENERGY ABSORBER SYSTEM DESIGN

Thus far the emphasis has been concentrated on the design of the frangible tube and die. As the amount of energy to be absorbed increases because of the high impact velocities and/or large weights, multiple tubes and multiple layers are required (due to L/D limitations imposed), resulting in additional superstructure for support. This more complex arrangement is defined as an energy-absorption system.

System Design Procedure

In the case of a nuclear airplane, the protected package is a reactor containment vessel, spherical in shape. When designing a frangible tube for protecting this package, a one-tube design would result in an operating angle limitation of $\pm 5^{\circ}$. It would, therefore, be desirable to use multiple tubes and support the tubes laterally. With multiple tubes the energy absorber operating angle may conceptually be increased to $\pm 30^{\circ}$. The requirement for protecting the containment sphere over a wide range of impact angles still dictates that the segments be repeated many times. An operating angle of $\pm 30^{\circ}$ requires 16 segments to protect the vessel in all directions.

A requirement of low g's in the package to be protected results in long strokes (energy absorber lengths). A limitation on the length to diameter ratio of the tube to prevent tubular column buckling is also added to the system complexity. Although no further tubes are necessary, a second bulkhead or structure plate is necessary for lateral support at an L/D of say 10. This adds to the system weight through additions of support structure.

A system design analysis, therefore, involves not only the tube and die design for optimum absorption of energy but the design of supporting structure for the transmission of the deceleration loads. All of these components add to the weight of the system and energy to be absorbed. Increasing the weight increases the kinetic energy and, according to equation (7), increases the number of tubes required.

System Design Characteristics

For the system analyzed in this report (i.e., a nuclear core surrounded by shielding and containment vessel), the design characteristics are as follows:

Weight of protected package, lb (kg)	50 000 to 400 000 (22 600 to 181 000)
Deceleration, g	140 to 600
Impact velocity profile, ft/sec (m/sec):	
In frontal direction	250 to 600 (76 to 183)
In all other directions	250 (183)
Sphere diameter, ft (m)	12 (3.67)
Number of segments	18 to 30
Tube material	Maraging steel (18 Ni maraging)
Tube specific energy, ft-lb/lb (J/kg)	40 000 to 90 000 (120 000 to 270 000)
Design ratio, t_t/R	0.6
Design ratio, D/R	8 to 12
Tube L/D limitation	10
Die design	See fig. 10
Die material	Plastic with steel liner
Die yield stress, psi (N/cm^2)	100 000 (68 900)
Die shear stress, psi (N/m^2)	100 000 (68 900)
Bulkhead wall thickness, in. (cm)	0.250 (0.635)
Bulkhead material	Plastic
Impact surface	Granite

System Design

In designing a system, the tube and die arrangement chosen reflect the configuration of minimum weight and reliable operation.

Review of candidate system designs. - In figure 4 a multilayer 4π protection (omni-

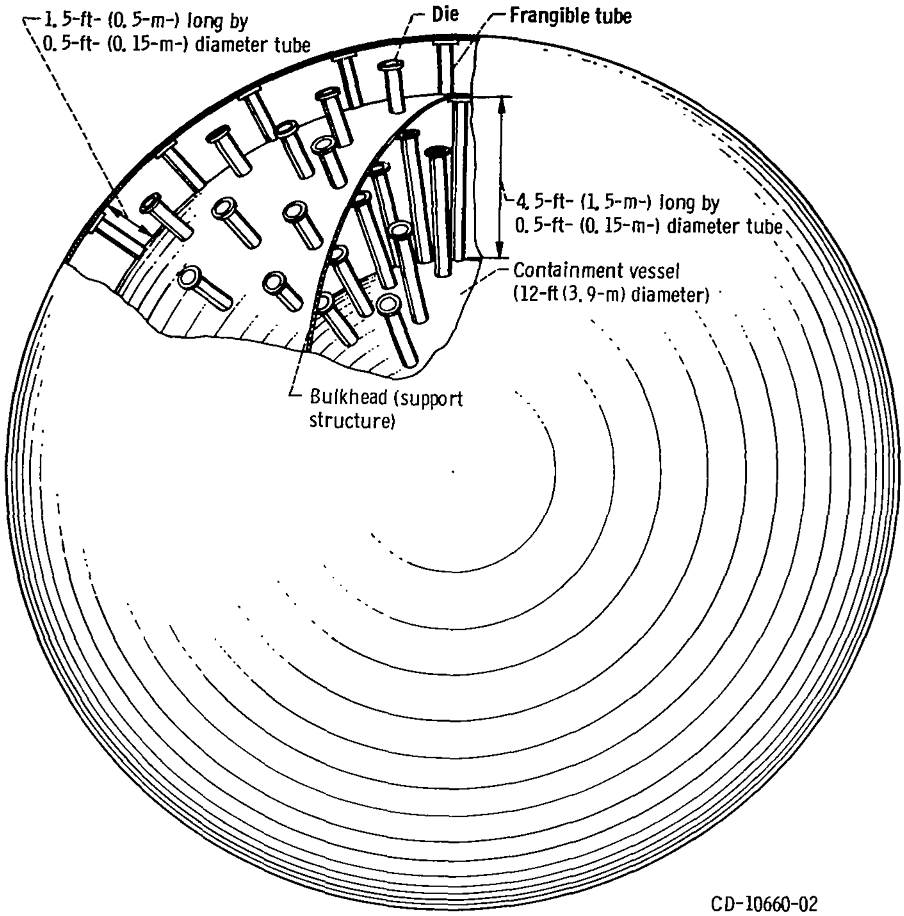


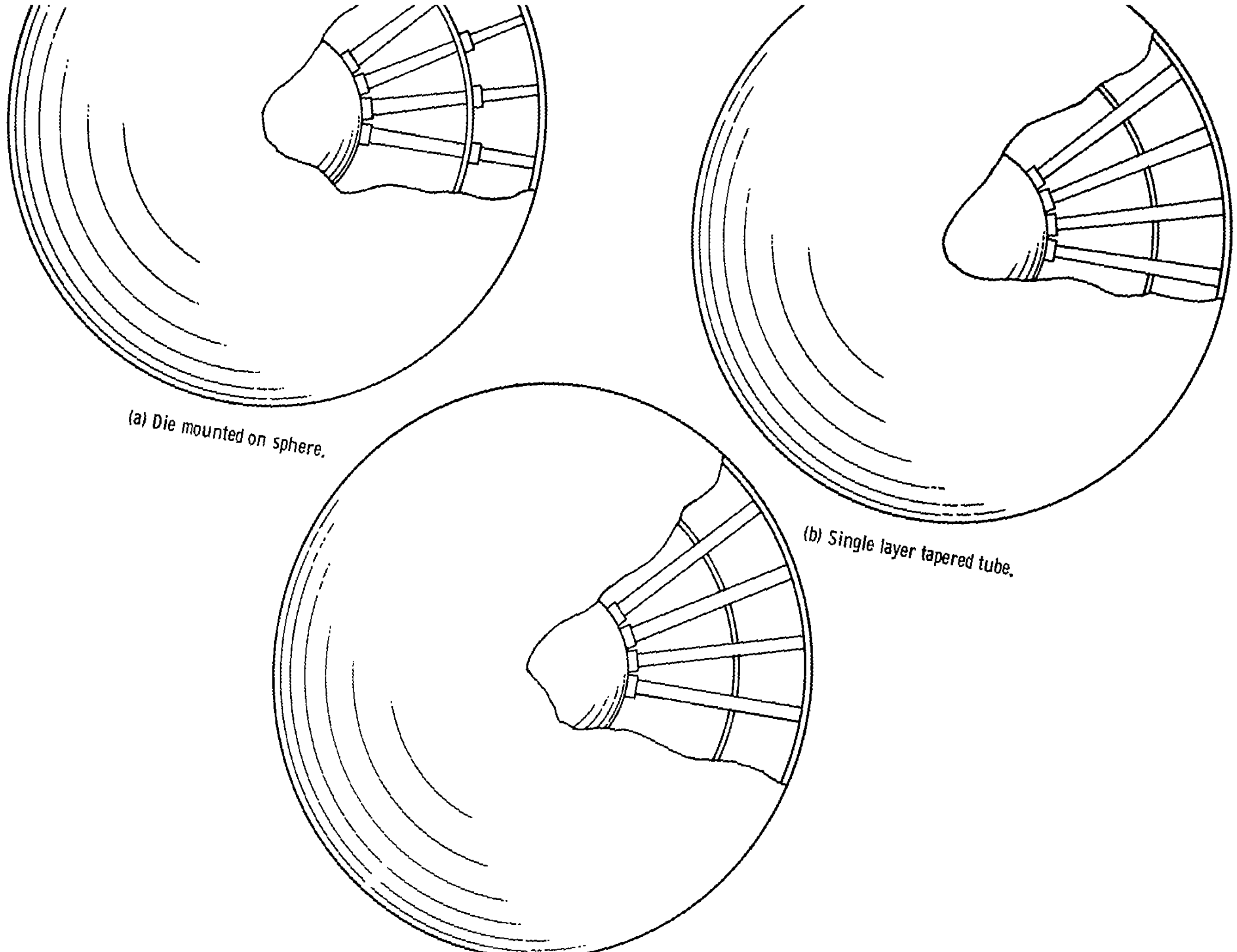
Figure 4. - Frangible tube system (4π protection).

directional) design is shown. Here the tubes are mounted on the sphere first and then the dies. Figure 5 shows schematically other arrangements. Figure 5(a) shows the dies reversed to that shown in figure 4. Figure 5(b) shows tapered tubes with one die and figure 5(c) shows an untapered tube. A detailed analysis of the directional problem may well show distinct advantages of one or more of these arrangements. They are presented here as but a few alternates to the arrangement analyzed in this report.

Design analysis. - The system design considered in this report contains the tube and die arrangement of figure 5(a). In this configuration the die is attached to the sphere with the tube extending radially outward.

The tubes are then attached for lateral support to a bulkhead or structural plate. Where multiple layers are necessary, a die is mounted on the bulkhead with a second tube extending radially outward to a second bulkhead.

The analysis has been programmed for a IBM 7094 computer (see appendixes A and B). This analysis provides for multiple grouping of tubes, each of which contains



(a) Die mounted on sphere.

(b) Single layer tapered tube.

(c) Single layer untapered tube.

Figure 5. - Various arrangements of frangible tubes.

CD-10661-02

multiple layers where required. Stress calculations are provided for the dies of each tube. Estimated weights are calculated for the additional superstructure that is required.

PARAMETRIC ANALYSIS OF SYSTEM

In designing a frangible-tube system there are design parameters that can be adjusted for the optimization of a minimum weight system. The purpose of this parametric analysis, then, is to determine (1) the minimum weight possible for the system, (2) the design parameters having the greatest effect on this weight, and (3) the design parameters having a lesser effect on this weight.

Description of Parameters

The parameters that form a part of the system to be analyzed are the number of segments, number of tubes per segment, specific energy of the tube, impact velocity, deceleration during impact, and ratio of frangible-tube diameter to die radius.

Number of segments. - Each group of tubes mounted radially on the sphere capable of absorbing the energy of impact is referred to as a segment. The greater the number of segments the greater the system weight but the smaller the included angle within which the tubes are required to operate (see fig. 6).

Number of tubes. - Within a segment there can be a variation in the number of tubes. With a few tubes their diameters, wall thicknesses, and dies are large. With many tubes their diameters, wall thicknesses, and dies are small.

Specific energy of tube. - The specific energy of the tubes dictates the total weight of tubes of each segment because the product of the total weight of the franged material and its specific energy must equal the kinetic energy the segment is to absorb. (The specific energy of the tube considers only the tube weight - not the die weight.)

Impact velocity. - For a given protected package weight the kinetic energy to be absorbed increases as the square of the impact velocity, thus, becoming an increasingly major contributor to the energy absorber weight.

Deceleration during impact. - At impact the impact velocity is reduced to zero at a predetermined rate or deceleration g. The higher the g values, the smaller the stroke. High g values, however, result in high forces, heavy support structures, and thick containment vessels. Low g's result in long strokes, resulting in more layers of energy absorbers (due to L/D limitations).

Ratio of frangible tube inside diameter to die forming radius, D/R. - The variation of this parameter affects primarily the die weight. As the tube diameter increases the

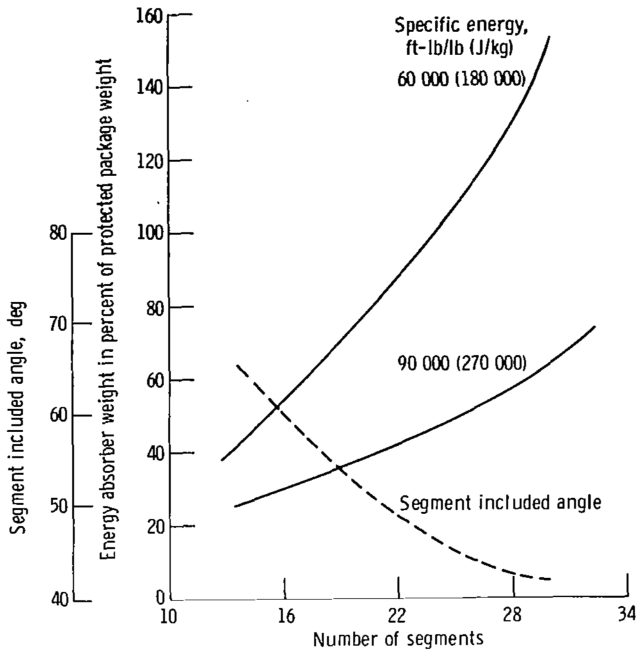


Figure 6. - Energy absorber weight and segment included angle as function of number of segments. Payload, 200 000 pounds (90 600 kg); deceleration, 300 g's; velocity profile, 400 feet per second (122 m/sec) ±30° from front and 250 feet per second (76 m/sec) in all other directions.

die diameter also increases, resulting in a weight addition as a function of the die diameter squared. Upon examination of all of these parameters a minimum weight system can be obtained.

Design Constraints and Assumptions

A minimum-weight energy-absorption system has been designed for protection of a typical nuclear reactor power source. The reactor would generate 300 megawatts of power and be applicable to a 1 million pound (4.5×10^5 kg) aircraft. The reactor core and shielding are surrounded by a large spherical containment vessel 12 feet (3.67 m) in diameter. The following assumptions were made in the design analysis:

(1) The frangible tubes are mounted on the surface of the sphere extending radially outward with the tube and die arrangement of figure 5(a).

(2) The energy-absorption system possesses an omnidirectional capability. This condition requires that the "protected package" be surrounded by energy absorbers in a 4π containment.

(3) The maximum impact velocities occur only in the frontal direction ($\pm 30^{\circ}$ solid angle). The remaining directions are capable of absorbing energies at impact velocities no greater than 250 feet per second (76 m/sec). The aircraft cruises at a velocity of 700 to 800 feet per second (214 to 244 m/sec).

(4) The segment impacting absorbs only 75 percent of the total energy of impact. The remaining 25 percent is absorbed by some of the redundant segments. During impact, the franging of the tubes in the impacted segment also results in the folding or collapsing of adjacent segments. The 75 to 25 percent assumption takes this energy absorbing process into consideration.

(5) No energy is absorbed by the air frame.

(6) No energy is absorbed by the containment vessel.

(7) Frangible-tube dies are fabricated from plastic material with a metal-lined forming radius.

(8) Plastic bulkheads are provided to absorb the lateral loads. Where strokes exceed an L/D of 10, multiple bulkheads are provided.

RESULTS

The preliminary analysis that was conducted is divided into two categories for discussion: (1) those design parameters having the greatest effect on the system weight, and (2) those design parameters having the lesser effect on system weight. All parameters studied, regardless of the category they fall in, were varied over a range considered to be within a reasonable extrapolation of existing state-of-the-art technology. The ranges of these variables were included in the System Design Specifications and Requirements section.

Design Parameters Having Greatest Effect on System Weight

The system design parameters which have the greatest effect on the energy absorber system weight are the number of segments (and subsequently the angular dependence of each segment), the specific energy of the frangible tubes, the frontal impact velocity, and the deceleration of the protected package.

Number of segments. - Figure 6 contains a plot of the energy absorber system weight in percent of protected package weight against the number of segments in the system. Specific energies of 90 000 foot-pounds per pound (270 000 J/kg) (a theoretical maximum value using maraging steel tubes) and 60 000 foot-pounds per second (180 000 J/kg) were considered. In addition, the segment included angle is plotted as a function of the number of segments. This angle represents the solid angular protection that one segment provides for the sphere. It also represents the maximum angular load that is applied to tubes in that segment.

The number of segments were arbitrarily varied over a large range. The result was that the energy absorber system weight increases sharply with the increase in the number of segments especially at lower specific energies. The segment included angle, however, decreases with increasing number of segments. The need for reducing lateral loading on the tube within the segment by increasing the number of segments thus is offset significantly by an increase in system weight.

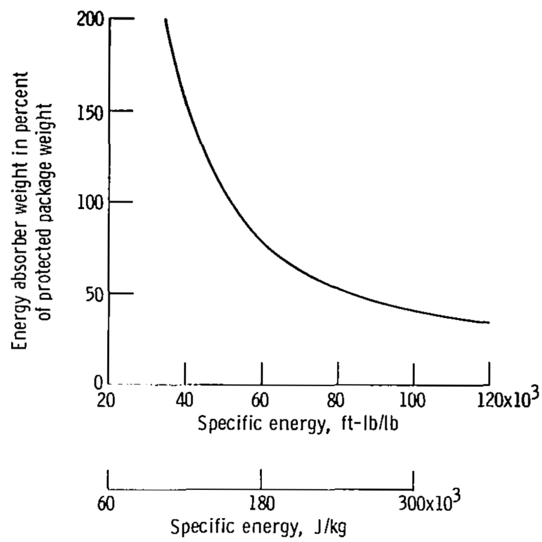


Figure 7. - Energy absorber weight as function of tube specific energy. Payload, 200 000 pounds (90 600 kg); deceleration, 150 g's; velocity profile, 250 to 400 feet per second (76 to 122 m/sec); segment operating angle, 46°; number of segments, 24; tube diameter to die forming radius ratio, 10.

Frangible-tube specific energy. - The effects of varying the frangible-tube specific energy in a system of 24 segments and at a 400 foot per second (122 m/sec) frontal impact velocity protection are illustrated in figure 7. At a frangible-tube specific energy of 90 000 foot-pounds per pound (270 000 J/kg) the energy absorber system weight is 46 percent of the protected package weight. This weight increases to 76 percent with a one-third reduction in specific energy to 60 000 foot-pounds per pound (180 000 J/kg). Further reductions in tube specific energies result in prohibitive weight penalties. The need for high specific energies is well illustrated in figure 7.

Frontal impact velocity. - The effects of increasing the frontal velocity under the same conditions of frangible-tube specific energy and 24 segments is illustrated in fig-

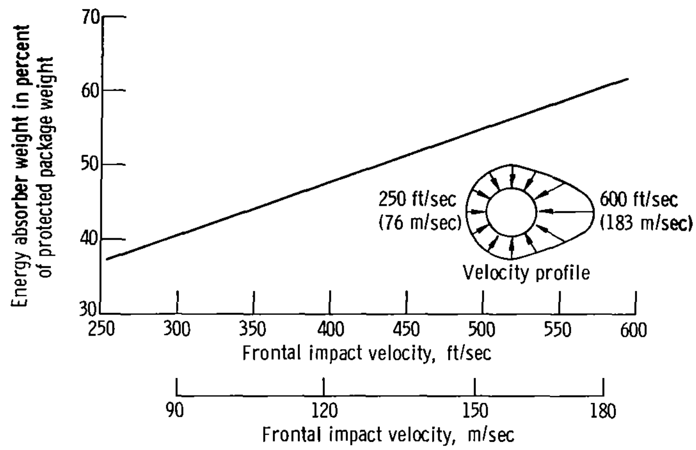


Figure 8. - Energy absorber weight as function of frontal impact velocity. All remaining directions are designed for impact velocity of 250 feet per second (76 m/sec). Payload, 200 000 pounds (90 600 kg); deceleration, 300 g's; segment operating angle, 46°; number of segments, 24; number of tubes, 40; specific energy, 90 000 foot-pounds per pound (270 000 J/kg).

ure 8. Increasing the frontal impact velocity from the minimum value of 250 to 600 feet per second (76 to 183 m/sec) increases the system weight by 68 percent.

Deceleration of protected package. - For the deceleration parameter, a minimum system weight is obtained at 250 g's. This can best be explained as follows. With a requirement of low g's the stroke (length of tube to be franged) must be large, thus requiring multiple layers. These layers add more dies and bulkheads to the system and thus more weight. Now as the deceleration values increase, the stroke is reduced. This condition eliminates bulkheads and dies, thus reducing the system weight. The increase in deceleration values, however, increases the force per tube requiring larger tube diameters, wall thicknesses, and die diameters, which thus increases the die weight. For example, a typical die weight at 140 g's of deceleration is 5.5 pounds (2.5 kg); this weight increases to 50 pounds (22.6 kg) at 600 g's. This increased die weight offsets the weight reduction due to fewer bulkheads.

Design Parameters Having Lesser Effect on System Weight

The second area of investigation was the design parameters which had the lesser effect on the energy absorber system weight. Two variables were analyzed - namely, the number of tubes per segment and the frangible-tube diameter to die radius ratio.

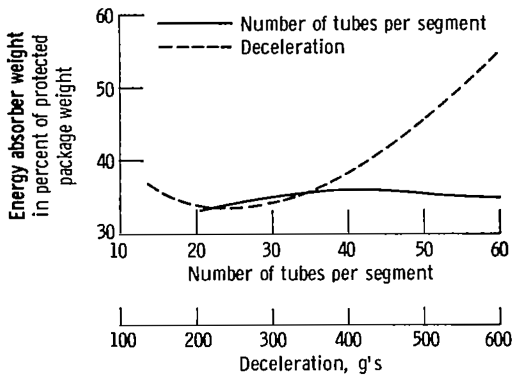


Figure 9. - Energy absorber weight as function of number of tubes per segment and package deceleration. Payload, 200 000 pounds (90 600 kg); velocity profile, 250 to 400 feet per second (76 to 122 m/sec); segment operating angle, 56°; number of segments, 18; specific energy, 90 000 foot-pounds per pound (270 000 J/kg).

Number of tubes per segment. - In the case of the number of tubes per segment, illustrated in figure 9, the curve is fairly flat showing that the minor weight penalty for increasing or decreasing the number of tubes per segment would be dictated by geometry and mechanical design considerations.

Frangible-tube diameter to die radius ratio. - The ratio D/R was varied between 8 and 12 at a constant t/R ratio of 0.6. These D/R values were recommended in reference 4 for best franging performance. The calculations showed that this parameter had no effect on the system weight. It was expected that as this ratio increased a reduction in system weight would occur, since large D/R ratios result in larger tube diameter, longer length tubes for a L/D of 10, and, subsequently, fewer layers, dies, etc. Between the range selected (8 to 12) this effect was either too slight to notice or was offset by increasing die weights.

DISCUSSION OF RESULTS

The parametric analysis reveals that using conventional energy absorbers, such as frangible tubes, results in high system weights. As an example, a typical 300-megawatt powerplant system design being studied at Lewis for application to a 1 million pound (4.53×10^5 kg) nuclear airplane has the following specifications:

Weight of powerplant (containment vessel, shielding, and core), lb (kg)	200 000 (91 000)
Impact deceleration, g	300
Impact velocity profile, ft/sec (m/sec)	
In frontal direction	400 (122)
In all other directions	250 (76)
Containment vessel diameter, ft (m)	12 (3.66)
Number of segments	24
Segment operating angle, deg	46
Number of tubes per segment	40
Specific energy of tubes, ft-lb/lb (J/kg)	90 000 (270 000)

The dies, bulkheads, etc. of the system were assumed to be fabricated from a high strength plastic material.

From the parametric curves, the resultant weight of this system is approximately 50 percent of the powerplant. The specific energy of the overall system is 1800 foot-pounds per second or only 2 percent of the assumed tube specific energy. The principal contributors to these large weights are the segment redundancy and the required superstructure (dies, bulkheads) which offset the high specific energy obtained from the tubes.

A more detailed design analysis of a frangible-tube system was not conducted. The reason is that, although the parametric analysis conducted herein was preliminary in nature, the design assumptions made were optimistic rather than conservative. As an example, tube specific energies to 90 000 foot-pounds per pound (270 000 J/kg) were used, plastic dies were assumed which are currently undeveloped, and thin plastic bulkheads were utilized for the lateral tube support and multiple layer application. A more detailed structural analysis may tend to increase the weight of these components and subsequently the overall weight of the system.

One area of consideration for weight reduction is the utilization of other reactor and airplane systems components as energy absorbers. An example would be the integration of the shielding as both a shield and energy absorber and use of the airframe to absorb some energy.

CONCLUDING REMARKS

The nuclear airplane must be safe. To meet this safety requirement the nuclear power source is protected at impact against release of fission products. Frangible-tube energy absorbers are candidate devices for this protection. Their recorded high specific energies of 38 500 foot-pounds per pound (115 500 J/kg) together with the potential for even higher specific energies are their major advantage. This specific energy, however, reflects only the tube weight and does not include die weight and associated structural weights.

Therefore, a parametric study was conducted for determining the weight of one energy-absorption system concept utilizing frangible tubes. The system typified that which might be applied to a nuclear airplane. The results of this study are as follows:

1. Decreasing the number of segments surrounding the sphere or increasing the specific energy of a frangible tube substantially decreases the energy absorber system weight. Variables of lesser effect but still of significance are the frontal impact velocity and the deceleration of the protected package.

2. Changing the number of tubes per segment or changing the design ratio of tube diameter to die radius has a minor effect on system weight.

The parametric analysis revealed that with frangible tubes the system weight in all cases was large. A typical 300-megawatt powerplant for a 1 million pound (4.53×10^5 kg) nuclear airplane would require an energy-absorption system weighing 50 percent of the powerplant weight.

Based on the parametric analysis, the following recommendations are made:

1. Other candidate systems should be studied before frangible-tube systems are looked at in more detail. The reason is that although the parametric analysis conducted was preliminary, the design assumptions made were optimistic rather than conservative. That is, the performance data of the tubes and support structure were assumed at their theoretical maximum values, resulting in a minimum system weight.

2. Methods must be studied in which the energy absorber is integrated with the shield, structural material, etc. In this manner the system components serve both as they are intended to be used during normal system operation and as an energy absorber during impact.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 17, 1969,
126-15.

APPENDIX A

DESIGN ANALYSIS

The design analysis developed for the energy-absorption system calculates (1) the size of the tube necessary to absorb the kinetic energy of the protected package and (2) the weight of the tube, die, and bulkhead which comprise the energy-absorption system. Since the tube, die, and bulkhead weights also become part of the weight of the package to be stopped, both calculations are dependent on each other.

Calculating Tube Size

To arrest a package in motion at a controlled magnitude of deceleration, it is necessary to oppose the motion with a force. This relation is

$$F = \frac{w_p}{g} a \tag{A1}$$

At the initial time at which the force is applied, the total energy the package possesses is expressed by

$$\text{Kinetic energy} = \frac{1}{2} \frac{w_p}{g} V_i^2 \tag{A2}$$

In the simple case where one franging tube provides the resisting force, the length of the tube franged must be

$$S = \frac{1}{2} \frac{w_p}{g} \frac{V_i^2}{F} \tag{A3}$$

when a constant force is assumed over the distance S.

With the equations of energy satisfied, it is now necessary to design a frangible tube which will provide a force F through a distance S. The franging stress of a tube is defined as

$$\sigma_F = \frac{F}{A_t} \tag{A4}$$

Some empirical relations of franging stress as a function of tube and die design are as follows:

$$\sigma_F = 1000\left(284.0\,\frac{t_t}{R} - 58.0\right) \tag{A5}$$

$$\sigma_F = \frac{1900\,\frac{D_t}{R} - 0.333}{0.7 - \frac{t_t}{R}} \tag{A6}$$

$$\sigma_F = 1000\left(2.21\,\frac{t_t}{R} - 1.1\right) \tag{A7}$$

Equation (A6) gives the franging stress for the 2024-T3 aluminum alloy which is taken from reference 4. Equations (A5) and (A7) are franging stress approximations for AISI 4130 steel and A231B magnesium alloy, respectively. Both equations were derived from graphs in reference 4.

When the franging stress (obtained from typical eqs. (A5) to (A7) or assumed) is known, the tube area is obtained by rearranging equation (A4):

$$A_t = \frac{F}{\sigma_F} \tag{A8}$$

The tube area is also related to the inside and outside tube diameters by

$$A_t = \frac{\pi}{4}\left(D_{o,t}^2 - D_{i,t}^2\right) \tag{A9}$$

Substituting $(D_{i,t} + 2t_t)$ for $D_{o,t}$ and solving for the wall thickness give

$$t_t = \sqrt{\frac{A_t}{\pi\left(\frac{D_{i,t}}{t_t} + 1.0\right)}} \tag{A10}$$

where $D_{i,t}/t_t$ is obtained from input parameters t_t/R and $D_{i,t}/R$.

In cases where the stroke S exceeds a tube length to diameter ratio of 10, a second tube is used. This requires the calculation of a final velocity for the first tube. Using the time motion equation the final velocity is

$$V_i^2 - V_f^2 = 2aS = \Delta(V^2) \tag{A11}$$

where

$$\Delta(V^2) = 2aS \tag{A12}$$

$$V_f = \sqrt{V_i^2 - \Delta(V^2)} \tag{A13}$$

Although V_f represents the final velocity for the first tube, it is the initial velocity for the second tube. This calculation continues until V_f is 0. At this point the total kinetic energy of the package has been expended by a franging force F through a stroke S.

An important parameter used in evaluating a frangible tube is the specific energy. The specific energy is defined as the amount of energy the tube is capable of absorbing per pound of tube. It is derived simply as follows:

$$\text{Specific energy} = \frac{\text{Energy absorbed}}{\text{Weight of tube}} \tag{A14}$$

For a tube force F acting through a franging stroke S

$$\text{spe} = \frac{FS}{\rho_t S A_t} \tag{A15}$$

Substituting equation (A8) for F

$$\text{spe} = \frac{\sigma_F}{\rho_t} \tag{A16}$$

Calculating System Weight

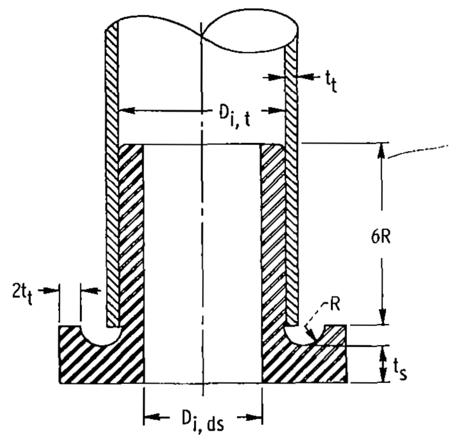
The system weight consists of the tubes, dies, and bulkheads of all segments surrounding the containment vessel. The weight is calculated by sizing the tubes and dies in each segment as if that segment were the one in which the impact occurred.

The weight of the tube is calculated by using the relation of the specific energy and the kinetic energy:

$$\text{Tube weight} = \frac{ke}{spe}\left(1 + \frac{6R}{S}\right) \tag{A17}$$

$$\text{Tube weight} = \frac{w_{sys}V_i^2}{2g\ spe}\left(1 + \frac{6R}{S}\right) \tag{A18}$$

The ratio 6R/S represents the percent of the tube unfranged due to the stroke bottoming on the die shank (see fig. 10). The quantity 6R/S adds to the franged tube weight which will remain unfranged.



Weight of die shank $= \frac{\pi}{4}\rho_d\left(D_{i,t}^2 - D_{i,ds}^2\right)(7R + t_s)$

Weight of die $= \frac{\pi}{4}\rho_d\left[(D_{i,t} + 4R + 4t_t)^2 - D_{i,t}^2\right](R + t_s) - \frac{1}{2}\pi^2R^2(D_{i,t} + 2R)$

Figure 10. - Frangible tube and die design dimensions.

When calculating the weight of the die, it is necessary to determine the wall thickness of the shank t_{ds} and the shear thickness t_s supporting the die forming radius R (see fig. 10). To determine these thicknesses accurately requires a complex stress analysis of the tube which is beyond the scope of this investigation. Therefore, a simple relation to porportion the surface pressure P applied to the die shank for all values of tube radius, wall thickness, and yield stresses was assumed to be

$$P = \frac{2t_t}{r_t}\sigma_y \tag{A19}$$

where P is the boundary pressure on the die shank attempting to collapse it and σ_y is the tube yield stress. The allowable boundary pressure for collapsing the shank is expressed by

$$P = \frac{t_{ds}}{r_{ds}} \left[\frac{\sigma'_y}{1 + 4 \frac{\sigma'_y}{E_{ds}} \left(\frac{r_{ds}}{t_{ds}} \right)^2} \right] \tag{A20}$$

(ref. 8) where σ'_y is the die yield stress. Setting equation (A19) equal to equation (A20) and solving for t_{ds} yield the cubic equation

$$X^3 + \frac{X}{C_1} = \frac{\sigma'_y}{\left(\frac{2t_t}{r_t} \right) \sigma_y C_1} \tag{A21}$$

where

$$X = \frac{r_{ds}}{t_{ds}}$$

$$C_1 = \frac{4\sigma'_y}{E_{ds}}$$

The required die shank wall thickness is given by $r_t = r_{ds} + t_{ds}$, which, after rewriting, becomes

$$t_{ds} = \frac{r_t}{(X + 1)} \tag{A22}$$

The shear thickness t_s is obtained in a more direct manner:

$$\left. \begin{aligned} \sigma_s &= \frac{F}{A_s} \\ t_s &= \frac{F}{2\pi r_{i,t} \sigma_s} \end{aligned} \right\} \tag{A23}$$

Finally, assuming a t_t/R of 0.6 the die forming radius R can be determined based on the tube thickness. The remaining dimensions used for the die are shown in figure 10. When these dimensions are used, the equation for computing the die weight is (see fig. 10)

Die weight = Weight of die shank + Weight of die base

$$= \frac{\pi}{4}\rho_d\left(D_{i,t}^2 - D_{i,ds}^2\right)(7R + t_s) + \frac{\pi}{4}\rho_d\left[(D_{i,t} + 4R + 4t_t)^2 - D_{i,t}^2\right](R + t_s)$$

$$- \frac{1}{2}\pi^2 R^2 (D_{i,t} + 2R) \qquad \text{(A24)}$$

The last component of the system for weight estimates is the bulkhead. This equation is simply

$$\text{Bulkhead weight} = \frac{4\pi r_b^2 t_b \rho_b}{N} \qquad \text{(A25)}$$

The total segment weight becomes

$$\text{Segment weight} = \text{Tube weight} + \text{Die weight} + \text{Bulkhead weight} \qquad \text{(A26)}$$

The total system weight is

$$\text{System weight} = \sum_{i=1}^{N} \text{Segment weight} + \text{Protected package weight} \qquad \text{(A27)}$$

APPENDIX B

PROGRAM LISTING

In designing an energy-absorption system for protecting a package, the process is complicated in that as energy absorbers are used to absorb kinetic energy, they too add to the overall weight of the system. For maximum design flexibility, the analysis is best accomplished on the computer using an iterative process.

The method of calculating an energy absorber using the equations of appendix A is summarized as follows:

(1) Calculate franging stress (see eqs. (A5) to (A7)) or designate a franging stress.

(2) Calculate specific energy (see eq. (A16)).

(3) Assume a system weight.

(4) Begin calculating segment weights.

(5) Begin calculating the first section weight of the first segment.

(6) Calculate the tube force (see eq. (A1)).

(7) Calculate the tube area, wall thickness, and outside diameter (see eqs. (A8) and (A10)).

(8) Calculate franging stroke when the tube $L/D = 10$.

(9) Calculate the final velocity of the layer (see eq. (A13)).

(10) Calculate the tube weights, due weights, and bulkhead weight of the section (see eqs. (A18), (A24), and (A25)).

(11) If the final velocity calculated in step (9) is not zero, return to step (5) and calculate the next section. Repeat until final velocity is zero.

(12) Sum all section weights for the segment (see eq. (A26)).

(13) Return to step (4) and calculate next segment. Repeat until all segments have been calculated.

(14) Sum weights of all segments for system weight (see eq. (A27)).

(15) Use new system weight for step (3) and repeat steps (4) to (14) until convergence. Convergence occurs when two successive system weights are within convergence tolerance.

The computer listing of the above calculations follows. All input and output are in U.S. customary units.

```
C     PARAMETRIC CODE SYSTEM 2
C
      DIMENSION DOT(30,10),DI(30,10),VELF(30,10),F(30,10),T(30,10),XL(30
     1,10),G(30,10),XNOT(30,10),R(30,10),S(30,10),TW(30,10),SWT(30,10),
     2DIFWT(30,10),BUWT(30,10),TS(30,10),TP(30,10),DID(30,10)
      DIMENSION VELX(30),SYSWT(30),PREV(30),NO(30)
      COMMON K,J,SIGF,SIGD,T,DI,SIGS,APT,ED,PI,TP,CHECKP,TS
C
      READ (5,101) KSIGMA,NOL,NOS
      READ (5,901) ((XNOT(J,K),K=1,NOL),J=1,NOS)
      READ (5,901) ((G(J,K),K=1,NOL),J=1,NOS)
      READ (5,901) (VELX(J),J=1,NOS)
      READ (5,901) RHO1,RHO2,RHO3,BHT
  101 FORMAT (8I10)
  901 FORMAT (8F10.7)
  907 FORMAT (5G20.9)
  904 FORMAT (11H1SECTION NO,10X,8HLAYER NO,12X,11HNO OF TUBES,9X,12HACC
     1ELERATION)
      WRITE ( 6,904)
      DO 908 J=1,NOS
      DO 909 K=1,NOL
  909 WRITE (6,907) J,K,XNOT(J,K),G(J,K)
  908 CONTINUE
  980 FORMAT (11HJSECTION NO,10X,11HINITIAL VEL)
      WRITE (6,980)
      DO 981 J=1,NOS
  981 WRITE (6,907) J,VELX(J)
  510 READ (5,901) DOVR,TOVR,PL,SIG,SIGD,SIGS,ED
  910 FORMAT (8HJRHO1 = G15.5,3X,7HRHO2 = G15.5,3X,7HRHO3 = G15.5,3X,7HD
     1OVR = G15.5/8HJTOVR = G15.5,3X,10HPAY LOAD =G15.5/12HJFRAN STR = G
     215.5,3X,12HDIE YIELD = G15.5,3X,12HDIE SHEAR = G15.5/15HJDIE MODUL
     3US = G15.5)
      WRITE (6,910) RHO1,RHO2,RHO3,DOVR,TOVR,PL,SIG,SIGD,SIGS,ED
C
      JO = 0
      PRE = 0.0
      PI= 3.14159
      DO 7 I=1,NOS
    7 SYSWT(I) = PL
  710 CONTINUE
      NXI  = 0
      SWTT= 0.0
      DO 711 J=1,NOS
      DO 711 K = 1,NOL
  711 S(J,K) = 0.
C
C     CALCULATE FRANGING STRESS
C
      GO TO (71,72,73,74,55),KSIGMA
   71 SIGF= (284.0*TOVR - 58.0)*1.0E+03
```

```
      GO TO 95
   72 SIGF= 1.9*1.0E+03*DOVR**.333/(.7-TOVR)
      GO TO 95
   73 SIGF= (2.21*TOVR-1.1)*1.0E+03
      GO TO 95
   74 SIGF= SIG
      GO TO 95
   95 CONTINUE
C
C     CALCULATE SPECIFIC ENERGY
C
      SPE= SIGF/(RHO1*12.0)
      DEBUG SIGF,SPE
      NX= 0
C     ************************************
C     SECTION ITERATION LOOP
C     ************************************
C
      DO 700 J=1,NCS
C
      NX= 1+NX
      DEBUG NX
      DEBUG SYSWT (J)
C
      NC(J) = 0
      NK= 0
C     ************************************
C     LAYER ITERATION LOOP
C     ************************************
      DO 500 K=1,NOL
C
      IF (J-1) 4,4,5
    4 IF (K-1) 2,2,3
    3 SYSWT(J) = SYSWT(J) - SWT(J, K-1 )
      IF(SYSWT(J).LT.PL) SYSWT(J)= PL
    2 GO TO 8
    5 CONTINUE
      IF (K-1) 8,8,10
   10 SYSWT(J) = SYSWT(J) - SWT(J, K-1 )
C
C     CALCULATE FORCE
    8 F(J,K)= SYSWT(J) * G(J,K)
C
C     CALCULATE TUBE AREA
      APT= F(J,K)/(SIGF * XNCT(J,K))
      DEBUG F(J,K),APT
C
C     CALCULATE TUBE THICKNESS
      DOVT = DOVR/TOVR
      T(J,K)= SQRT(APT/(PI*(DOVT + 1.0)))
C
C     CALCULATE INSIDE DIAMETER
C
      DI(J,K)= DOVT* T(J,K)
      R(J,K)= T(J,K)/TOVR
      DEBUG DOVT,T(J,K),DI(J,K)
```

```
C
C     CALCULATE OUTSIDE DIAMETER
C
      DOT(J,K)= DI(J,K) + 2.0*T(J,K)
C
      NC(J) = 1 + ND(J)
C
   12 XLOVD= 10.0
      XL(J,K)= XLOVD * DOT(J,K)
      S(J,K)= XL(J,K)/12.0
      DELV= 2. * G(J,K) * S(J,K) * 32.2
      DEBUG S(J,K),DOT(J,K),DELV
C
C     CALCULATE FINAL VELOCITY
C
      IF(K-1) 15,15,14
   15 VELFX= VELX(J)**2 - DELV
      IF(VELFX.LT.0.0) GO TO 17
      VELF(J,K)= SQRT(VELFX)
      DEBUG VELF(J,K)
      GO TO 400
   17 DELV= VELX(J) **2
      NK= 1
      S(J,K)= DELV/(2. * G(J,K) * 32.2)
      VELF(J,K)= 0.0
      GO TO 400
   14 VELFX= VELF(J, K-1 )**2 - DELV
      IF(VELFX.LT.0.0) GO TO 18
      VELF(J,K)= SQRT(VELFX)
      DEBUG VELF(J,K)
      GO TO 400
   18 DELV= VELF(J, K-1 )**2
      NK= 1
      S(J,K)= DELV/(2.*G(J,K)*32.2)
      VELF(J,K)= 0.0
      DEBUG S(J,K)
C
C     CALCULATE TUBE WT
C
  400 IF(K-1) 20,20,21
   20  TW(J,K) = (SYSWT(J)*(VELX(J)**2 - VELF(J,K)**2))/(64.4*SPE)*(1.+6
     1.*R(J,K)/(S(J,K)*12.))
      DEBUG TW(J,K)
      GO TO 29
C
   21 TW(J,K) = (SYSWT(J)*(VELF(J,K-1)**2-VELF(J,K)**2))/(64.4*SPE)*
     1(1.+6.*R(J,K)/(S(J,K)*12.))
      DEBUG TW(J,K)
   29 CONTINUE
C
C     CALCULATE DIE WT
C
      CALL DIESTR
C
   25 DIEW=RHO2*.25*PI*((DI(J,K)**2-DID(J,K)**2)*(7.*R(J,K)+TS(J,K))+(((
     1DT(J,K)+4.*R(J,K)+4.*T(J,K))**2-DI(J,K)**2)*(R(J,K)+TS(J,K)))-2.0*
```

```
     2PI*R(J,K)**2*(DI(J,K)+2.*R(J,K)))
      DEBUG DIEW
      DIEWT(J,K)= DIEW * XNOT(J,K)
C
C     CALCULATE BULKHEAD WT
      RADX = 0.
      DO 405 I =1,NOL
  405 RADX = RADX + S(J,I)
      AREAX = 4./FLOAT(NOS) *PI*(RADX + 6.0)**2
      BUWT(J,K) = AREAX*BHT*RHO3 *144.
      DEBUG BUWT(J,K)
C
C     CALCULATE SYSTEM WT
C
      SWT(J,K)= TW(J,K) + DIEWT(J,K) + BUWT(J,K)
      DEBUG SWT(J,K)
C
   31 IF (NK) 500,500,600
C
  500 CONTINUE
C
C
  600 CONTINUE
C
      TUW= 0.0
      DIFT= 0.0
      BUT= 0.0
      NOX = NO(J)
      DO 30 K=1,NOX
      TUW = TUW + TW(J,K)
      DIFT= DIFT + DIEWT(J,K)
   30 BUT= BUT + BUWT(J,K)
C
      IF(J-1) 40,40,41
   40 SYSWT(J)= (DIFT + BUT + TUW) + PL
      GO TO 42
   41 SYSWT(J)= (DIFT + BUT + TUW)
   42 DEBUG SYSWT(J)
C
C
  700 CONTINUE
      DO 701 I = 1,NOS
  701 SWTT = SWTT + SYSWT(I)
C
      ERR= ABS(SWTT - PRE)/SWTT
      PRE= SWTT
      IF (ERR.GT..01) GO TO 702
      GO TO 703
  702 NXL= 1
  703 CONTINUE
      DEBUG SWTT
      DO 781 I = 1,NOS
  781 SYSWT(I) = SWTT
      IF(SWTT.GT.5.0E+05) GO TO 705
      JO = 1 + JO
      IF (NXL) 705,705,710
```

```
  705 CONTINUE
  912 FORMAT(11HLSECTION NO,10X,8HLAYER NO,12X,14HTUBE THICKNESS,6X,12HO
     1UTSIDE DIAM,8X,9HFINAL VEL)
      WRITE(6,912)
  914 FORMAT (6G20.9)
      DO 913 J=1,NCS
      NOX = NO(J)
      DO 913 K=1,NOX
  913 WRITE (6,914) J,K,T(J,K),DOT(J,K),VELF(J,K)
  921 FORMAT(11HLSECTION NO,10X,8HLAYER NO,12X,10HDIE RADIUS,10X,5HFORCE
     1,15X,11HTUBE LENGTH,18X,1HS)
      WRITE (6,921)
      DO 922 J=1,NCS
      NOX = NO(J)
      DO 922 K=1,NOX
  922 WRITE (6,914) J,K,R(J,K),F(J,K),XL(J,K),S(J,K)
C
  801 FORMAT (11HLSECTION NO,10X,8HLAYER NO,12X,10HSECTION WT,10X,6HDIE
     1WT,14X,11HBULKHEAD WT,9X,7HTUBE WT)
      WRITE (6,801)
      DO 802 J=1,NOS
      NOX = NO(J)
      DO 802 K=1,NOX
  802 WRITE (6,914) J,K,SWT(J,K),DIEWT(J,K),BUWT(J,K),TW(J,K)
  815 FORMAT (11HLSECTION NO,10X,8HLAYER NO,12X,14HDIE WALL THICK,6X,15H
     1DIE SHEAR THICK)
      WRITE (6,815)
      DO 816 J=1,NOS
      NOX = NO(J)
      DO 816 K=1,NOX
  816 WRITE (6,914) J,K,TP(J,K),TS(J,K)
  803 FORMAT (17HJTOTAL SYS  WT = G15.5,4X,16HFRANGE STRESS = G15.5,4X,1
     18HSPECIFIC ENERGY = G15.5)
      WRITE (6,803) SWTT,SIGF,SPF
      WRITE (6,914) JO
      GO TO 510
      END
```

```
      SUBROUTINE DIESTR
C
C
      DIMENSION DOT(30,10),DI(30,10),VELF(30,10),F(30,10),T(30,10),XL(30
     1,10),G(30,10),XNOT(30,10),R(30,10),S(30,10),TW(30,10),SWT(30,10),
     2DIEWT(30,10),BUWT(30,10),TS(30,10),TP(30,10),DID(30,10)
      DIMENSION VELX(30),SYSWT(30),PREV(30),NO(30)
      COMMON K,J,SIGF,SIGD,T,DI,SIGS,APT,ED,PI,TP,CHECKP,TS
C
      XC1= 4.*SIGD/ED
      DEBUG XC1
      A= 1.0/XC1
      DEBUG A
      XC2= -SIGD/(4.*T(J,K)/DI(J,K)*SIGF*XC1)
      DEBUG XC2
      B= XC2
      DUM= SQRT(B**2/4.+A**3/27.)
      DEBUG DUM
      BIGA= (-B/2.+DUM)**.333
      DEBUG BIGA
      VAR= (-B/2.-DUM)
      BIGB= SIGN(ABS(VAR)**.333,VAR)
      DEBUG BIGB
      X= BIGA + BIGB
      CHECKP= 1./X*SIGD/(1.+XC1*X**2)
      DEBUG CHECKP
C
      TP(J,K)= DI(J,K)/(2.*(X+1.))
      DEBUG TP(J,K)
      DID(J,K)= DI(J,K)-2.*TP(J,K)
C
C     CALCULATE DIE SHEAR THICKNESS TS
C
      XLOAD= SIGF*APT
      TS(J,K)= XLOAD/(SIGS*PI*DI(J,K))
      DEBUG TS(J,K)
C
      RETURN
      END
```

REFERENCES

.. Esgar, Jack B.: Survey of Energy - Absorption Devices for Soft Landing of Space Vehicles. NASA TN D-1308, 1962.

2. Daigle, D. L.; and Lonborg, J. O.: Evaluation of Certain Crushable Materials. Tech. Rep. 32-120, Jet Propulsion Lab., California Inst. Tech., Jan. 13, 1961.

3. Coppa, Anthony P.: Collapsible Shell Structures for Lunar Landings. Paper 2156-61, ARS, Oct. 1961.

4. McGehee, John R.: Experimental Investigation of Parameters and Materials for Fragmenting-Tube Energy-Absorption Process. NASA TN D-3268, 1966.

5. Hwang, C. S.: Energy Dissipation With Frangible Tubing. Univ. Texas, Feb. 1965. (Contract NAS-1-2817.)

6. Kartluke, Herbert; and Luckhardt, Philip G.: Development of an Energy Dissipation System Based on Metal Extrusion. Technidyne, Inc. (NASA CR-81317), Nov. 1966.

7. Anon.: Energy Absorber Squeezes Rings to Cushion Shocks. Product Eng., vol. 39, no. 9, Apr. 22, 1968, pp. 46-48.

8. Roark, Raymond J.: Formulas for Stress and Strain. Third ed., McGraw-Hill Book Co., Inc., 1954.

9. Smith, Ronald H.: The Design and Development of Radio Frequency Transparent, Omnidirectional, Energy-Absorbing Element Systems. Rep. NVR-5014, Northrop Corp. (NASA CR-66301), Jan. 1967.

NASA-Langley, 1970 —— 32 E-4991

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546

OFFICIAL BUSINESS

FIRST CLASS MAIL

POSTAGE AND FEES PAI
NATIONAL AERONAUTICS
SPACE ADMINISTRATIO

05U 001 47 51 3DS 70058 00903
AIR FORCE WEAPONS LABORATORY /WLCL/
KIRTLAND AFB, NEW MEXICO 87117

ATT E. LOU BOWMAN, CHIEF, TECH. LIBRARY

POSTMASTER: If Undeliverable (Section 1 Postal Manual) Do Not Re

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546